Concrete-steel bond influence in the cyclic response of RC structural elements

Humberto Varum[1,a], Aníbal Costa[1,b], Hugo Rodrigues[1,c] and Catarina Fernandes[1,d]

[1]Civil Engineering Department, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

[a]hvarum@civil.ua.pt, [b]acosta@civil.ua.pt, [d]hrodrigues@aveiro-norte.ua.pt, [d]cfernandes@civil.ua.pt

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Abstract. Poor bond conditions are a frequent cause of damage of collapse of reinforced concrete structures under cyclic loading, such as the induced by earthquakes. Reinforced concrete elements built with smooth plain reinforcing bars are particularly sensitive to bond-slip and to its effects. A simplified numerical model to account for the bond-slip effects is proposed. A numerical analysis was performed with the objective of evaluating the bond-slip influence in the dynamic response of a reinforced concrete frame, representative of existing structures built in Europe in the 50's~70's with smooth plain reinforcing bars. Based on the available experimental results the proposed model was calibrated.

Introduction

Recent earthquakes from all over the world, and particularly in Southern European countries, confirm the high seismic vulnerability of existing reinforced concrete (RC) buildings. Being the most common type of construction, they constitute an important source of risk for the society and can cause enormous economic losses and a large number of casualties in future events. Among others, bond-slip is a frequent cause of damage and collapse of RC structures under seismic loads. RC elements built with smooth plain reinforcing bars are particularly sensitive to bond-slip and to its effects. An important number of existing RC structures in Southern Europe were constructed in the 1950's~1970's using smooth plain reinforcement steel bars, with poor bond conditions. Therefore, the inclusion and calibration of the bond-slip effect in the numerical models is vital, so that a more realistic description of the cyclic behavior and the ultimate capacity of RC structures under seismic loading can be achieved.

Causes of damage and collapse of existing RC buildings under seismic loads

The seismic vulnerability of RC buildings is deeply related to the structural systems and constructive typologies characteristics. The most frequent causes of damage and collapse of RC structures due to earthquakes are associated to the following effects/mechanisms [1]: i) stirrups/hoops, confinement and ductility; ii) bond, anchorage, lap-splices and bond-splitting; iii) inadequate shear capacity and failure; iv) inadequate flexural capacity and failure; v) inadequate shear strength of the joints; vi) influence of the infill masonry on the seismic behavior of frames; vii) vertical and horizontal irregularities; viii) effect of higher modes; ix) strong-beam weak-column mechanism; and x) structural deficiencies due to architectural requirements.

Concrete-steel bond. Bond between concrete and reinforcing steel bars plays a fundamental role in the response of RC elements, particularly for cyclic loading, by allowing the stress transfer from the steel bars to the surrounding concrete. Perfect bond is usually assumed in the analyses of RC structures, implying full compatibility between concrete and reinforcement strains. However, this assumption is only valid for early loading stages and low strain levels. As the loads increases, cracking and breaking of bond unavoidably occurs and relative slip between the concrete and the reinforcing bars (*bond-slip*) takes place in the structural elements. Different strains are observed in the steel bars and in the surrounding concrete, and the stress distribution is affected in both materials [1].

Bond-slip effects are particularly significant in elements built with smooth plain reinforcing bars and for cyclic loading induced, for example, by earthquakes. In this situation, the concrete-steel bond can deteriorate even before the stress state has attained the steel yielding stress or the concrete strength [2]. RC elements built with smooth plain reinforcing steel bars are particularly sensitive to bond-slip and to its effects. Since a significant number of existing RC structures in Southern European countries were built in the 50's~70's using this type of bars, the thorough study of the bond-slip influence on their response to cyclic loads is particularly important.

Bond-slip modeling: a proposed simplified approach

Several authors point out the importance of considering bond-slip in the numerical models of analysis of RC structures. As stated by Monti and Spacone [3], the introduction of bond-slip of reinforcing bars in the numerical models proves to be a necessary enhancement towards a realistic description of the cyclic behavior and the ultimate capacity of reinforced concrete structures. A simplified approach to consider the bond-slip effect in the numerical models consists in adjusting the steel reinforcement constitutive laws with a global slippage factor [1].

When perfect bond is assumed between concrete and steel longitudinal bars, both concrete (c) and steel (s) fibers located at the same depth y have the same strain (ε):

$$\varepsilon_s = \varepsilon_c = \varepsilon \tag{1}$$

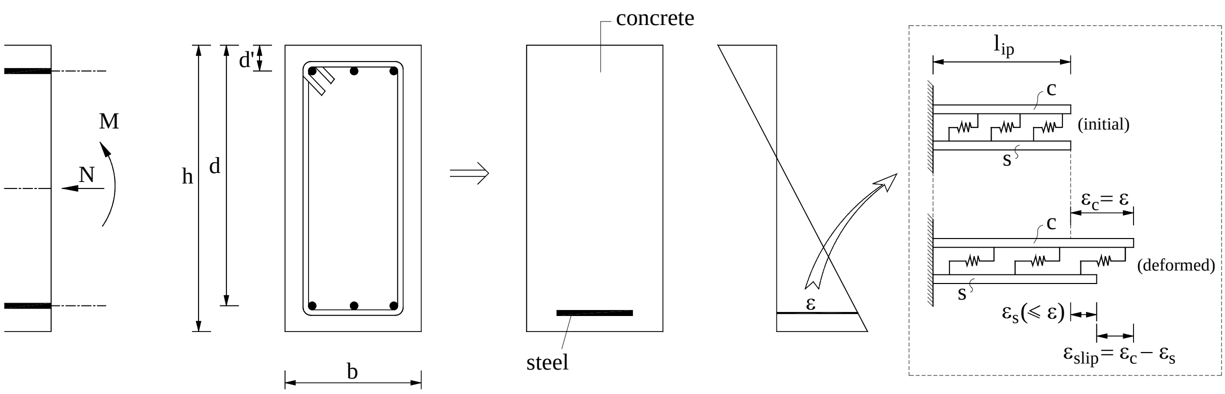

Fig. 1 Bond-slip deformation on the constituent materials [1].

Though, this assumption is no longer valid when bond-slip occurs (see Fig. 1). To account for bond-slip, a correction factor, S (see Eq. 2), is applied to the steel reinforcement constitutive law [1]. Basically, the correction is carried out by purely adjusting the characteristics of the monotonic steel behavior law. Considering that steel hardening strain in not reached, the steel constitutive law can be assumed as a bi-linear law with an elastic perfect plastic behavior (see Fig. 2) [1].

Considering bond-slip, the strain, stress and modulus of elasticity of the steel, are expressed by Eq. 3 to 5, respectively. The slippage factor S assumes the value 1.0 when perfect bond between steel and concrete is verified (see Eq. 6).

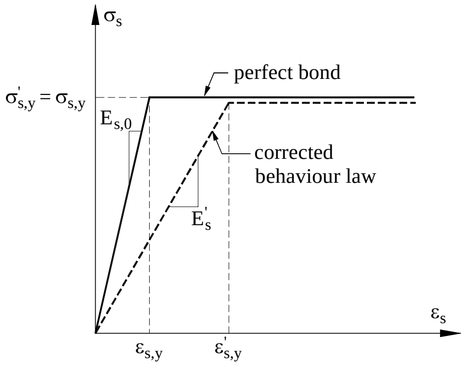

Fig. 2 Correction of the reinforcing steel constitutive laws [1].

$$S = \frac{\varepsilon_c}{\varepsilon_s} \qquad \varepsilon'_{s,y} = S \cdot \varepsilon_{s,y} \qquad \sigma'_{s,y} = \sigma_{s,y} \qquad E'_s = \frac{1}{S} \cdot E_{s,0} \qquad (2, 3, 4, 5)$$

$$\sigma_s(\varepsilon_s) = \begin{cases} if\ perfect\ bond & \begin{cases} \varepsilon_s < \varepsilon_{s,y} \leftarrow \sigma_s(\varepsilon_s) = E_{s,0} \cdot \varepsilon_s \\ \varepsilon_s \geq \varepsilon_{s,y} \leftarrow \sigma_s(\varepsilon_s) = \sigma_{s,y} \end{cases} \\ if\ not\,(not\ yielding\ steel\ occurs) & \leftarrow \sigma_s(\varepsilon_s) = \frac{1}{S} \cdot E_{s,o} \cdot \varepsilon_s \end{cases} \qquad (6)$$

Influence of the bond-slip in the dynamic response of RC structures: case study

A numerical analysis on a full-scale RC frame built with smooth plain reinforcing bars was performed with the objective of evaluating the influence of bond-slip in its response under simulated seismic loads.

General description of the structure. The 4-storey RC frame under study (see Fig. 3) was built, under the ICONS research program [1], and tested for several levels of seismic intensities. The structure was built with smooth plain reinforcing bars and can be considered representative of the design and construction common practice until the late 1970's in Southern European countries. Detailed information about the RC frame dimensions and characteristics, detailing, material properties, static and earthquake loads, and experimental test results, can be found in [1].

Fig. 3 RC frame under analysis [1].

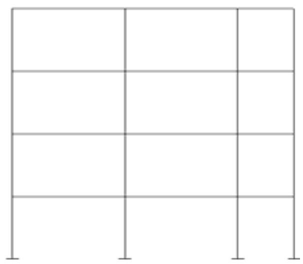

Fig. 4 General geometry of the frame in the numerical model.

Numerical model. A non-linear numerical model of the structure was developed using the non-linear analysis software VISUALANL [4]. All parameters which characterize the non-linear behavior of the elements at section level were computed with the BIAX software [5]. The general geometry of the frame is represented in Fig. 4. All geometric characteristics of the elements cross-sections, materials properties, loads and further information considered, can be found in [1,6].

Bond-slip modeling. Bond-slip effects were taken into account by using the simplified approach previously described. Several levels of slippage were considered by reducing the modulus of elasticity of the reinforcing steel in the constitutive law of each RC element. The corresponding slippage factor was calculated using Eq. 5. The element behavior curve, in terms of bending moment-curvature relation, was computed by the BIAX software, considering and not considering the bond-slip mechanism (see example in Fig. 5-a). A trilinear behavior curve was adopted for each element, from BIAX (see [6] and example in Fig. 5-b].

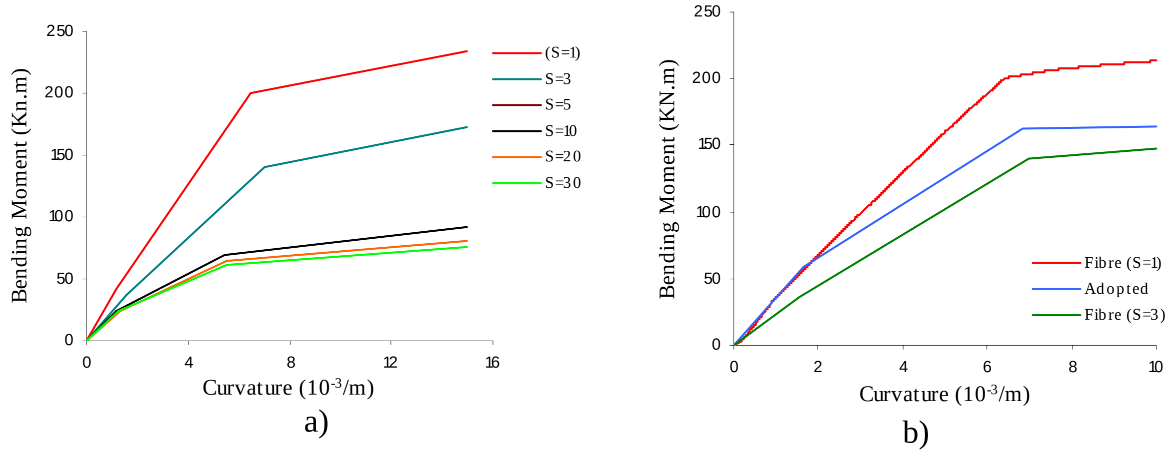

Fig.5 Monotonic behavior curve of a column: a) various levels of slippage; b) example of the adopted curve [6].

Influence of bond-slip in the dynamic response. In the numerical analysis described in [1] concerning the behavior of the RC frame under study, Varum [1] concluded that only with the inclusion of the bond-slip effect in the numerical models it was possible to well reproduce the experimental test results.

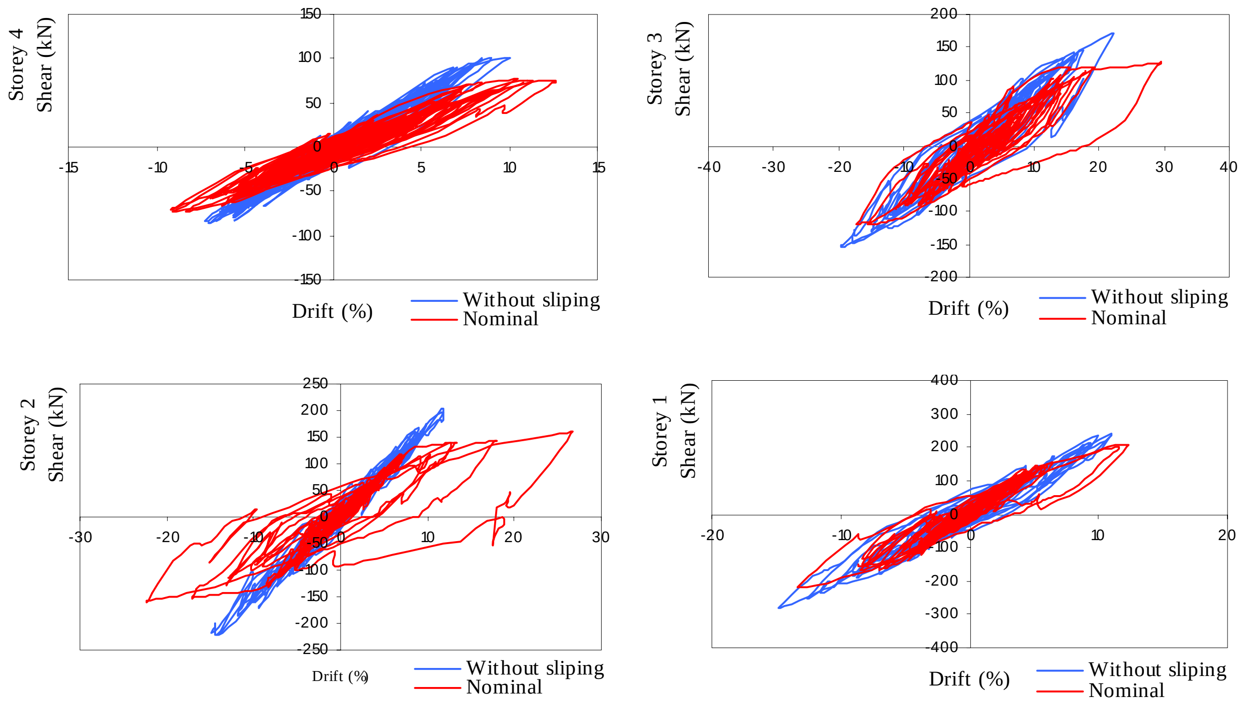

Fig. 6 Storey shear-drift response, considering and not considering the bond-slip mechanism [6].

Fig. 6 shows the results of analysis performed about the influence of bond-slip in the structural response of the RC frame under seismic loading. The results are presented in terms of storey shear-drift response, considering and not considering the bond-slip mechanism. The presence of bond-slip leads to a significant increasing of drift demand (150%) in storey 2. The maximum drift variation in storey 3 and storey 4 are 32% and 26%, respectively. Storey 1 is the less sensitive to the bond-slip effects.

Conclusions

Considering bond-slip in the numerical models for analysis of RC structures leads to a more realistic description of their cyclic behavior, as exemplified by the performed analysis on a 4-storey full-scale structure. A large test campaign on full-scale single structural elements is currently being prepared. RC elements (beams, columns and beam-column joints) built with smooth plain bars will be tested under cyclic loading and the influence of bond-slip in the response will be thoroughly evaluated.

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